FINAL TECHNICAL REPORT

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Rapid Finite Fault Inversion for Earthquakes in Southern California Using the Cybershake Library of 3D Green's Functions: Collaborative Research with AECOM and California State Polytechnic University in Pomona

Principal Investigators:

Dr Hong Kie Thio[1], Dr Jarmila Polet[2]

Telephone number and email address:

[1]AECOM Technical Services
300 S Grand Ave
Los Angeles, CA 90071

[2]Geological Sciences Dept
California State Polytechnic University
3801 West Temple Avenue
Pomona, CA 91768

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ABSTRACT

We developed a system for rapid finite fault inversion for intermediate and large Southern California earthquakes using local and teleseismic seismic waveforms as well as geodetic data and, where applicable, 3D Green's functions from the Cybershake project. The ultimate aim of this work is to provide these finite fault models within a few hours after an earthquake has occurred, so that they may be used as input to various post-earthquake assessment tools such as ShakeMap, as well as by the scientific community and other interested parties. Additionally, a systematic determination of finite fault models also has value as a resource for scientific studies on detailed earthquake processes, such as rupture dynamics and scaling relations.

One of the major hurdles in using local and regional data is that the dominant waves propagate primarily through the crust, so that heterogeneities, which are strong in the upper crust in particular, cause severe complications in the waveforms compared to simple 1-D propagation models, especially at shorter periods. Conventional inversions using 3D Green's functions help solve that problem, but their computation is too time-consuming to be used in a near real-time system. We therefore propose to use the pre-computed 3D Green's functions and procedures developed for the Cybershake project (Graves et al., 2010) as input to the inversion.

We have used our established least-squares finite fault inversion method that has been applied extensively both on large as well as smaller regional earthquakes, in conjunction with the Cybershake 3D Green's functions, where available, as well as 1D Green's functions for areas for which the library has not yet been developed. The aim is to create a system that will operate in near real-time and provide reliable finite fault models for moderate to large earthquakes in southern California. Results sofar indicate that the current library of Green's functions is marginally suited for finite fault source inversions using local data due to the course grid sampling at distances greater than 10 km. A denser grid of Green's function points and vertical components would greatly improve the feasibility of this project.

1 Introduction

1.1 Background

In the last few decades, routine global earthquake source analysis has evolved from the determination of first order parameters, such as hypocenter location and magnitude, to more comprehensive analyses including mechanism and more recently finite rupture models. These improvements are instrumental in the determination of more sophisticated earthquake impact assessment products such as ShakeMap and PAGER, which in turn provide invaluable information for post-event response to authorities and other stakeholders. For large global earthquakes these types of procedures are currently carried out by the National Earthquake Information Center of the USGS and collaborating scientists using mostly teleseismic waveforms. However, smaller earthquakes, for which global finite fault analyses using teleseismic data are not possible, can also be very destructive, as illustrated recently by the 2011 M_W= 6.3 Christchurch earthquake, and the November 9 M_w=5.6 aftershock of the 2012 Van earthquake. These events caused widespread damage and casualties in the city of Christchurch and Van respectively. An even smaller earthquake, the 2011 M_W=5.1 Lorca, Spain event caused significant damage and loss of life in the town of Lorca. Using regional and local data for rapid source inversions in Southern California is therefore an important addition to the routine earthquake analysis process and our goal for this project is to develop a system to achieve this in near real-time.

1.2 Project

Recent technological advances and the availability of high quality seismic and geodetic data in real-time now enable us to carry out comprehensive analyses of earthquake processes within hours of the event occurrence. Such efforts are ongoing, in particular at the USGS National Earthquake Information Center (NEIC) for large global earthquakes, but for smaller earthquakes (5<M<7), which can be just as devastating if located in urban areas, we have to rely on local and regional data for sufficient resolution. We propose to develop a system for routine finite fault inversions that will yield a model of the spatio-temporal characteristics of the earthquake using a large variety of available far-field and near-fielddata and a database of 3D local Green's functions, which are essential for wave simulations at shorter periods, and has already been developed for the Southern California Earthquake Center (SCEC) Cybershake project. Because we are using pre-computed 3D Green's functions, we will be able to operate this system in near real-time. The future direction in seismic wave propagation methodology is clearly aimed at the routine use of 3D Green's functions, with the simultaneous development of community velocity models (e.g. Plesch et al., 2009) as well as the Cybershake platform for efficient generation of Green's functions and their use in seismic hazard analysis (Graves et al., 2010).

2 Inversion Methodology

2.1 Finite Source Inversion

WE invert seismic and geodetic data for fault slip using the multiple-time window algorithm of Thio et al. (2004), which is a modified form of Hartzell and Heaton (1983). A least squares inversion with mixed constraints is applied using Lawson and Hanson (1974). The rake angle of the slip can vary within +/- 45°of the initial rake angle. We apply a smoothing constraint, but no damping constraint on the slip. We used square sub-faults of 2 by 2 km grid covered a depth range from 0 km at the trench to 45 km deep along the subduction interface. A more detailed description of the inversion procedure can be found in Thio et al (2004).

2.2 3D-Green's functions

The near-field Green's functions, or more accurately Strain Green's Tensors (SGT's) were recomputed and made available by SCEC (Callaghan, pers. comm.). In Figures 1 and 2 we present the stations and points for which Green's functions were computed. The Green's functions can be divided into two types:

- Background sources – these were calculated on regular grids with variable spacing depending on distance. Within a distance of 10 km, the horizontal grid spacing is 1 km and approximately 1.3 km beyond that distance.
- Fault sources – the discrete fault planes are sampled at significantly higher density than the background seismicity.

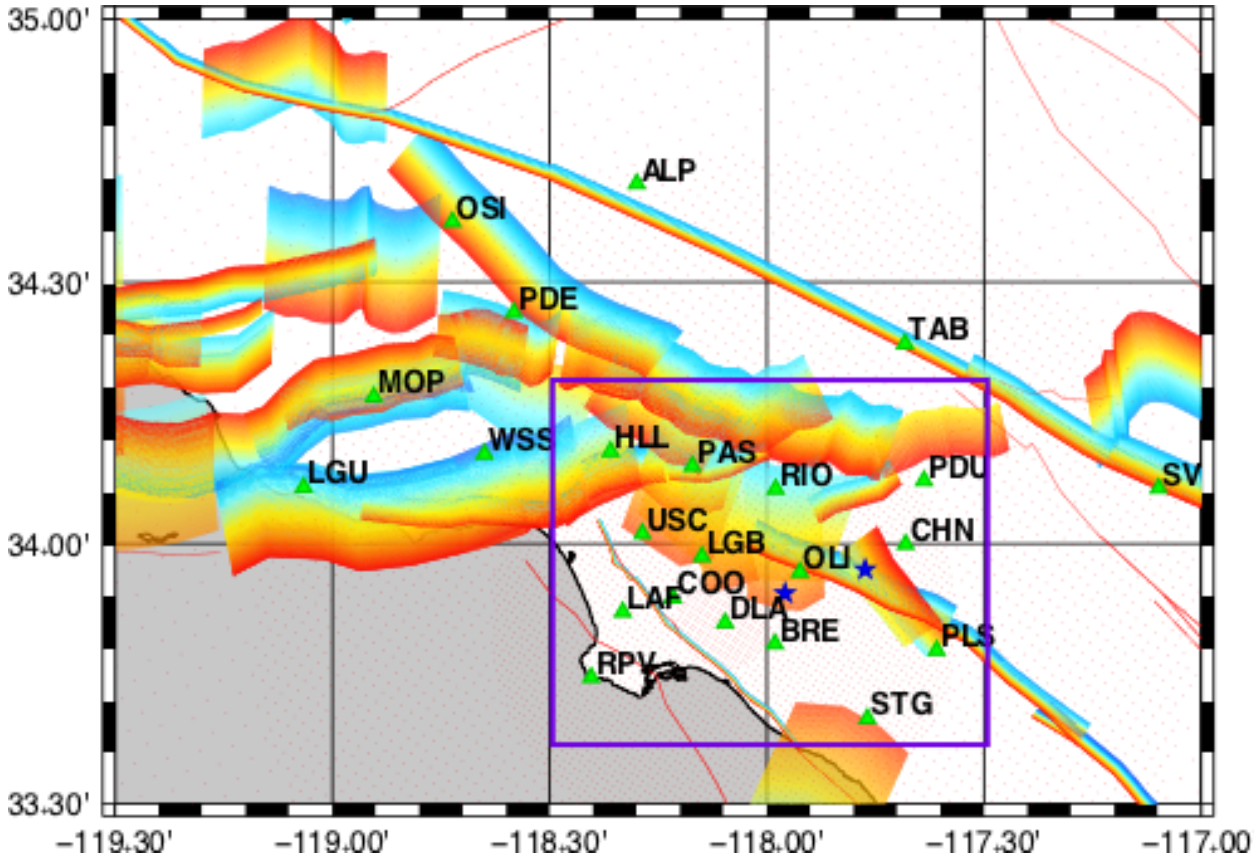

Figure 1. Map of Southern California showing the extent of the Cybershake domain. The rainbow-colored planes are the faults, with the colors indicating depth of the source. The evenly spaced dots are the background sources. Green triangles are the station locations for which the Green's functions were computed. The purple box shows the extent of Figure 2.

For each station, the total size of the Green's function library for the two horizontal components and the sources shown in Figure 1 amounts to 1.6 Gb approximately. For 22 stations, this adds up to 35 Tb, which posed a challenge both in terms of transmitting the data over the internet as well as storage on local computers (Callaghan et al., 2009). Aside from its original intent for numerical PSHA (Graves et a., 2010) this library has already been used for several other projects of scientific and engineering interest (e.g. Taborda et al., 2014, Bose et al., 2014).

2.3 Teleseismic Green's functions

The computation of teleseismic Green's functions using a hybrid combination of propagator matrices and teleseismic ray computations is well–established and widely used (e.g. Kikuchi and Kanamori, 1991) and can be carried out in a fully automatic manner. The algorithm is sufficiently fast that in the current implementation of our inversion code these Green's functions are computed during each run. The synthetic waveforms form a complete set of P-SV and SH arrivals for a stack of layers in the source region.

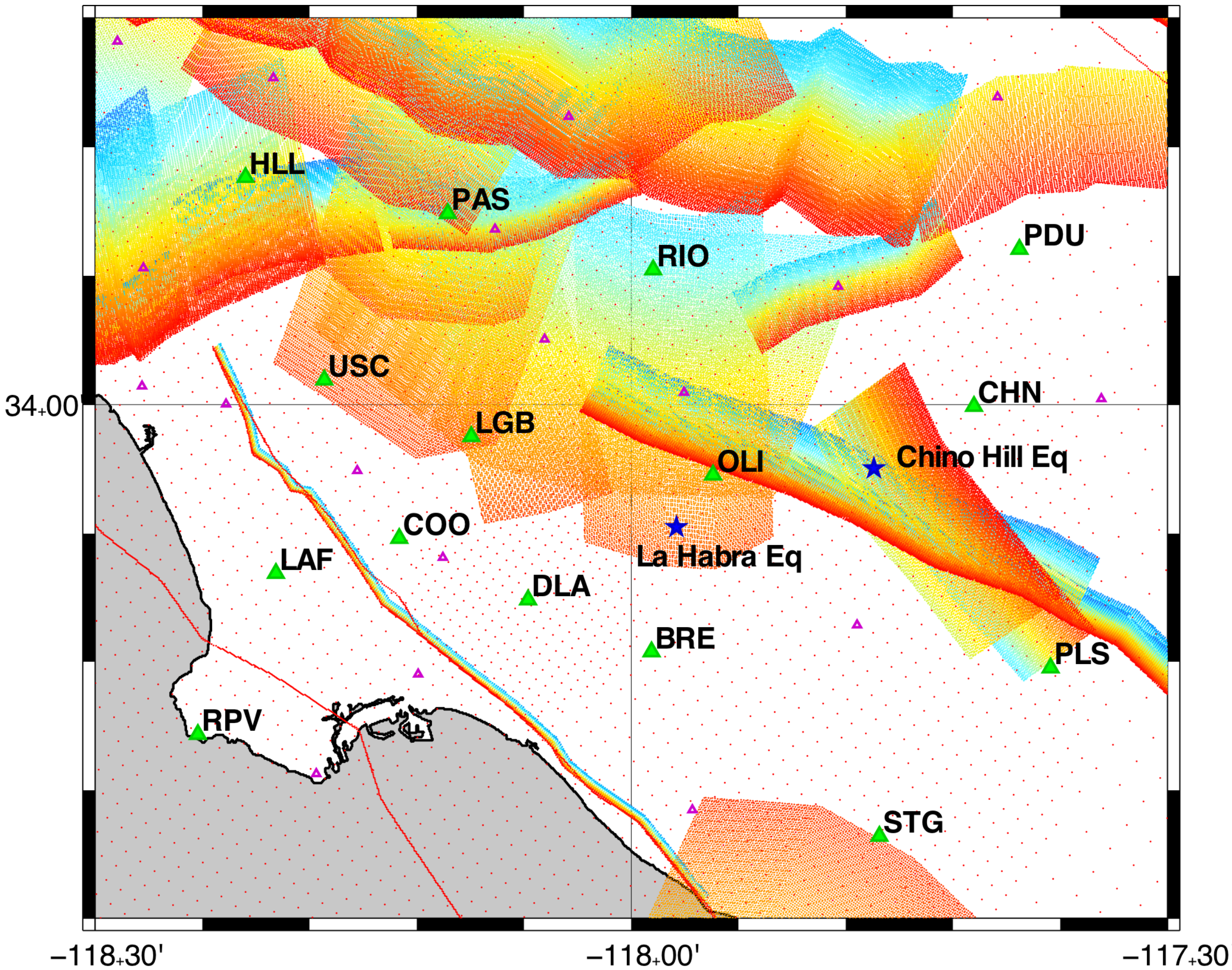

Figure 2. Enlargement of the LA Basin are from Figure 1. Also shown in small purple triangles are station locations for which data for the La Habra earthquake was obtained but for which no 3D Green's functions were available. The Chino Hills and La Habra earthquakes are shown as blue stars. The background grid locations are for station DLA.

2.4 Geodetic Green's functions

The static displacement fields can be computed in a variety of ways. Okada (1985) derived an analytical solution for computing the displacement field of a rectangular fault. A drawback to this method is that it only valid in half-spaces and Wald and Graves (2001) found that the advantage of the analytical solution was negated by the use of a half-space and that methods, even if approximate, using layered media gave preferable results. We therefore prefer the use of a frequency-wave-number integration technique (FK) developed by Wang et al. (2003, 2006).

3 Test event

3.1 The 2008 Chino Hills earthquake

The 2008 Chino Hills earthquake (M_W=5.4) is the largest earthquake in the greater Los Angeles Basin in the last two decades. Although it was felt over a wide region, it only caused minor damage in the epicentral area.

The earthquake appears to be related to the Yorba Linda trend identified by Hauksson et al (2008) and not to any of the nearby mapped faults. Therefore, for the Green's functions we use the background set rather than one of the denser fault sets.

The earthquake was recorded at a large number of stations (Figure 2) locally, approximately half for which we have 3D Green's functions.

3.2 Data

3.2.1 Local seismograms

The earthquake was well-recorded by the local SCSN network, including all stations for which 3D Green's functions are available (Figure 2). For this study, we initially concentrated our attention to the stations that are within 20 km of the earthquake to reduce the number of data, since this still leaves us with sufficient azimuthal coverage of the earthquake. However, it was immediately clear that the spacing of the Green's functions in most cases is too large for a source inversion, for which timing of the seismic phases is critical, even in a relative sense. Only for the shortest distance window is the density of source points sufficient. If the event had occurred on one of the pre-defined faults, the sampling would have been more than sufficient, but both for this event and the La Habra event, this is not the case. We were therefore left with only two stations that we could use for the inversion, CHN and OLI.

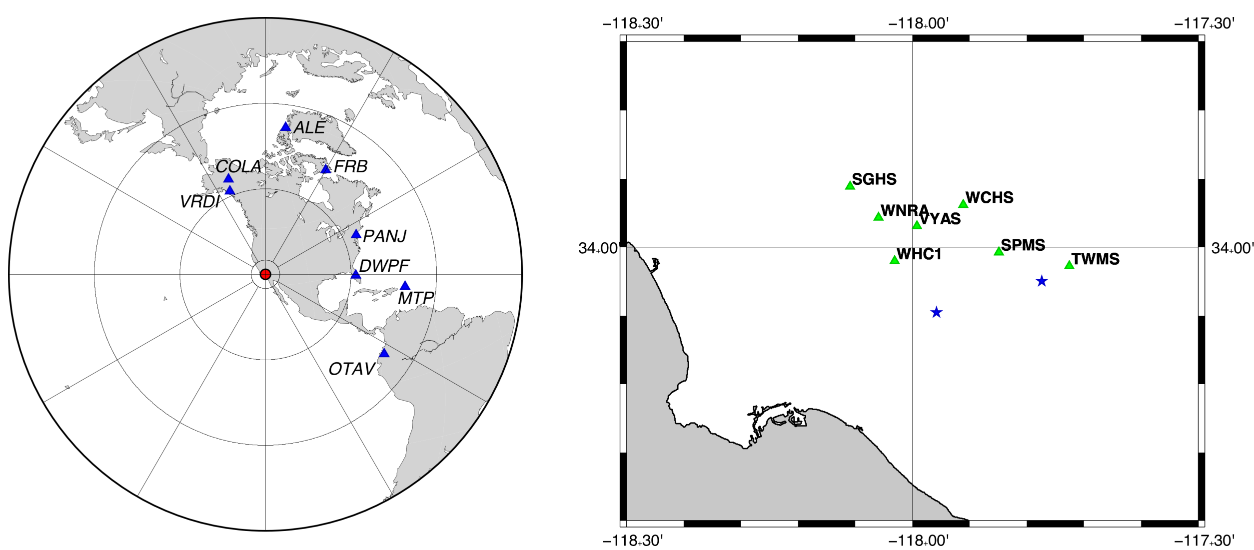

Figure 3. a (left) Map centered on the Chino Hill earthquake showing the locations of the available P-wave data. b (right) Locations of the GNSS sites for which displacement data is available for the Chino Hills earthquake.

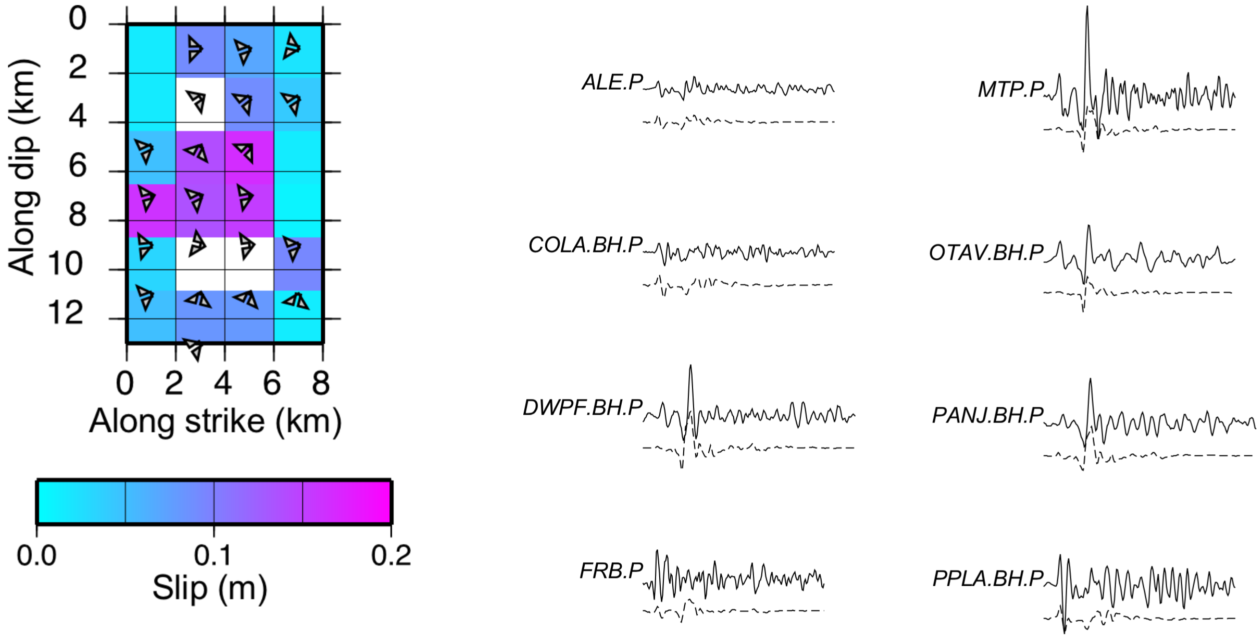

Figure 4. a (right) Slip map of the Chino Hills earthquake from the inversion of local teleseismic and geodetic data. b (left) Comparison of data and synthetic wave forms for this solution.

3.2.2 Teleseismic data

We collected teleseismic data in the distance range of 30 to 90 degrees, corresponding to P and S wave rays that bottom in the mantle and are therefore relatively simple to model accurately. Only a small percentage of the stations (~20 out of more than 500) yielded useable P waves, and after removing closely spaced stations we were left with 9 stations, shown in Figure 3a. Fortunately, these provide a reasonable azimuthal coverage, considering the fact that Pacific island stations are invariably too noisy for such small events.

3.2.3 Geodetic data

Nearby geodetic data available through UNAVCO are shown in Figure 3b. Given the size of the earthquake, only a few nearby stations yielded usable data but these provide valuable constraints to the solution. Since we are only using the static offset, we can compute the response for a simple layered model and are not bound by the limitations of the 3D Green's function sampling.

3.3 Inversion results

The results of the slip inversion of the above data for the Chino Hill earthquake is shown in Figures 4a. The pattern is relatively simple with the main slip at the hypocenter, which is not consistent with the observations of Hauksson et al (2008). An example of the waveform fits are presented in Figures 4b and 5, which shows a good agreement between observed and synthetic waveforms and displacement vectors. The solution was obtained using 10 windows with time step of .25 sec. This resolution in time is necessary to resolve details in the source

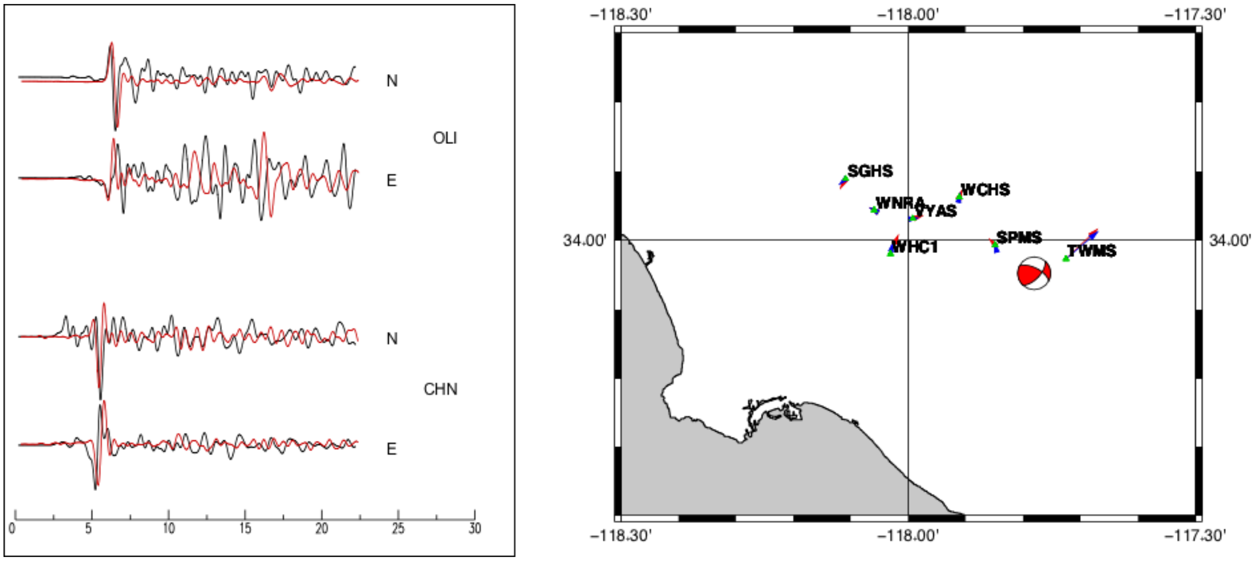

Figure 5. Observed and synthetic local waveforms (left) and geodetic displacement vectors (right). Black waveforms are data, red observed. For the geodetic vectors, red is data and blue synthetic.

process, which means that the current problem, with just two local stations and horizontal components only, is over-parametrized.

4 Discussion

4.1 Results

We have shown that it is feasible to use a combination of local 3D Green's functions and other data to determine slip distributions for small earthquakes. It is unlikely that this method will yield results for events smaller than magnitude 5, both because of the density of grid points for which Green's functions are available but also because of the density of stations.

4.2 Future improvements

In order to develop a routine system for finite-source inversions for small to intermediate earthquakes in Southern California, several improvements would be desirable. For the 3D Green's functions these are:

- Increase the number of stations for which Green's functions are pre-computed – this will double the coverage in the LA Basin and with the current distance-dependent gridding scheme improve the spatial resolution of the inversion system.
- Add vertical component – this will improve the resolving power of the inversion

In order to make these improvements possible on the current system, it is necessary to reduce the number of grid points on the faults, which greatly reduces the storage space needed (35 Tb currently), without sacrificing the effectiveness of the method.

To improve the system operationally, it would be useful to systematically analyze which teleseismic stations are likely to produce useable data for small events in Southern California thereby reducing the need to filter through large amounts of teleseismic data.

5 Acknowledgments

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6 References

Böse, M., R. W. Graves, D. Gill, S. Callaghan, and P. J. Maechling (2014), CyberShake-derived ground-motion prediction models for the Los Angeles region with application to earthquake early warning, *Geophys. J. Int.*, *198*(3), 1438–1457, doi:10.1093/gji/ggu198.

Callaghan, S. et al. (2009), Scaling up workflow-based applications, *Journal of Computer and System Sciences*, 1–19, doi:10.1016/j.jcss.2009.11.005.

Goulet, C. A., N. A. Abrahamson, P. G. Somerville, and K. E. Wooddell (2015), The SCEC Broadband Platform Validation Exercise: Methodology for Code Validation in the Context of Seismic-Hazard Analyses, *Seismol. Res. Lett.*, *86*(1), 17–26, doi:10.1785/0220140104.

Hauksson, E., K. Felzer, D. Given, M. Giveon, S. Hough, K. Hutton, H. Kanamori, V. Sevilgen, S. Wei, and A. Yong (2008), Preliminary Report on the 29 July 2008 Mw 5.4 Chino Hills, Eastern Los Angeles Basin, California, Earthquake Sequence, *Seismol. Res. Lett.*, *79*(6), 855–866, doi:10.1785/gssrl.79.6.855.

Lee, E.-J., P. Chen, T. H. Jordan, and L. Wang (2011), Rapid full-wave centroid moment tensor (CMT) inversion in a three-dimensional earth structure model for earthquakes in Southern California, *Geophys. J. Int.*, *186*(1), 311–330, doi:10.1111/j.1365-246x.2011.05031.x.

Taborda, R., and J. Bielak (2014), Ground-Motion Simulation and Validation of the 2008 Chino Hills, California, Earthquake Using Different Velocity Models, *Bull. Seismol. Soc. Am.*, *104*(4), 1876–1898, doi:10.1785/0120130266.

Thio, H. K., R. W. Graves, P. G. Somerville, T. Sato, and T. Ishii (2004). A multiple time window rupture model for the 1999 Chi-Chi earthquake from a combined inversion of teleseismic, surface wave, strong motion, and GPS data, *J. Geophys. Res. B Solid Earth Planets*, doi:10.1029/2002JB002381.

Wald, D. J., and R.W. Graves (2001). Resolution Analysis of Finite Fault Source Inversion Using 1D and 3D Green's Functions, Part II: Combining Seismic and Geodetic Data, J. Geophys. Res., 106, 8767.

Zhao, L., P. Chen, and T. H. Jordan (2006), Strain Green's Tensors, Reciprocity, and Their Applications to Seismic Source and Structure Studies, *Bull. Seismol. Soc. Am.*, *96*(5), 1753–1763, doi:10.1785/0120050253.